Distributed Architectures for Mars Surface Exploration

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Outline

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Building a Distributed System
Major Trades
Trade Study Process
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Motivation

Distributed systems may offer

- Energy efficiency (multi-hop vs. single hop)
- Distributed data collection and sensing
- Scalability, flexibility, robustness
- Support for robotic and human explorers

Mechanism(s)

- Spatial distribution of (homogeneous or heterogeneous) system elements
- Ability to reconfigure system (compensate for changes in environment, missions goals, or capabilities)

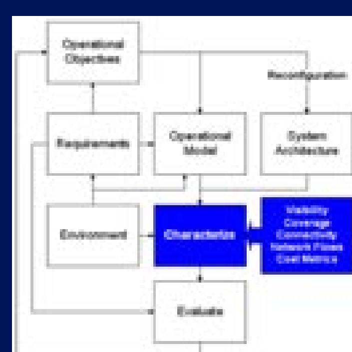
Modeling Distributed Systems

Surface model: digital elevation model

System element (node, agent, etc.) model

Analysis needs

- Connectivity
  - line-of-sight metric
  - Apply graph theory tools
- Surface visibility
- Cost of message delivery
- Cost of node mobility
- Model of system evolution



Surface Modeling and Characterization

Power spectral density characterization

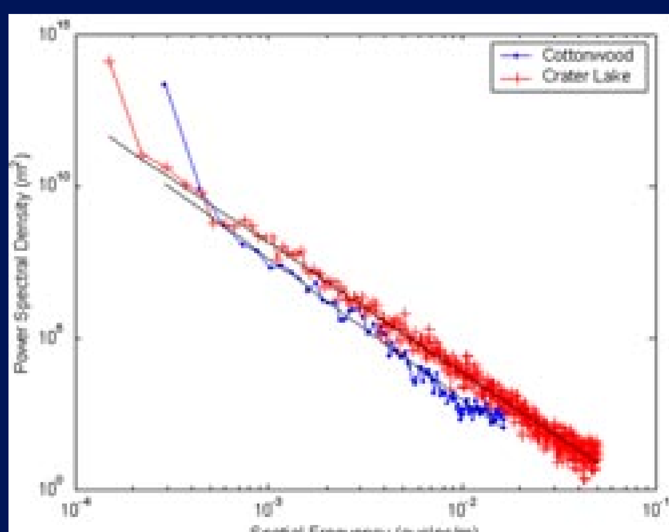
- Power law scaling exponent (3-5 normal range)
- Holds over several orders of magnitude
- Can use to generate random terrain

Height-height correlation function

Height autocorrelation function

Surface roughness or slope

Power Spectral Density of Terrain



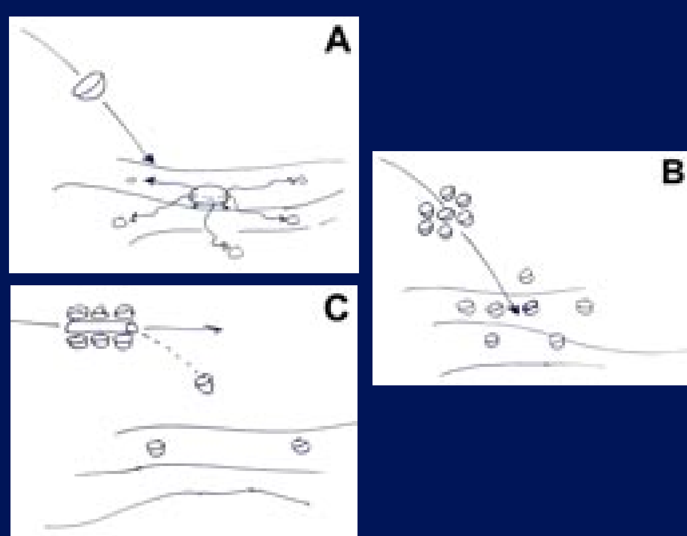
Trades

Distributed vs. Non Distributed
Delivery Mechanism
Multi-Hop vs. Single-Hop
Network Protocol Stack →
Quality of Service
- Delay
- Bandwidth

Network Stability
Node Heterogeneity
Required network services
- Timing
- Positioning
- Concurrency Control
- Data storage/access

Layer	Adjustable Parameters
Session	Timing and duration, Message content, Reassembly process
Transport	Routing, Transfer rate and latency, Network congestion control
Logical Link	Error control Flow control
Medium Access	Access timing and duration, Collision avoidance, Error avoidance
Physical	Radio Frequency Power, Antenna Gain, Pointing Requirements

Delivery Mechanism(s)



Single Hop vs. Multi Hop

FRIIS Transmission equation

Transmitted power, single hop $P_{t,s} \propto (nr)^m P_r$

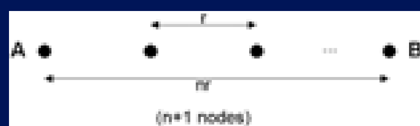
Transmitted power, multi hop $P_{t,m} \propto nr^m P_r$

m is space loss exponent (2 for free space)

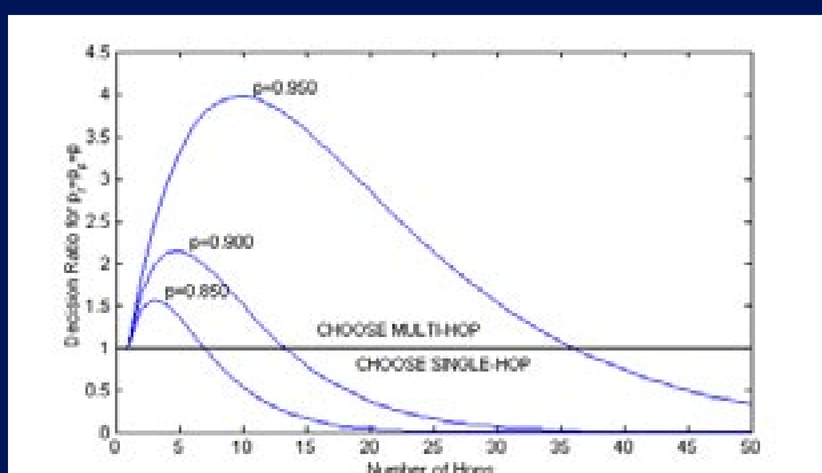
Prob(send message|received) p_s

Prob(receive message|sent) p_r

Ratio of expected power for delivery via multi-hop to single hop $\frac{E(P_{t,s})}{E(P_{t,m})} = (p_s p_r)^{n-1} n^{m-1} = K$



Single Hop vs. Multi Hop



Network Topology Study

Hypothesis

The **degree distribution** of the graph that characterizes the connectivity of a distributed system is likely to be shifted towards higher degrees as **node density** increases and as the **power law scaling exponent** increases. Coverage, measured as a percentage of the surface covered, is likely to improve as the power law scaling exponent increases and as the number of nodes increases.

Network Topology Study

Methods (Topography Study)

Create terrain

- power spectral density terrain generation approach
- power law scaling exponent (beta) = 3,4,5
- 100 trials per condition

Distribute nodes

- 20 nodes distributed randomly on surface

Compute network topology

- Line-of-sight visibility used as connectivity metric
- Compute degree distribution

Network Topology Study

Methods (Node Density Study)

Create terrain

- power spectral density terrain generation approach
- power law scaling exponent (beta) = 4

Distribute nodes

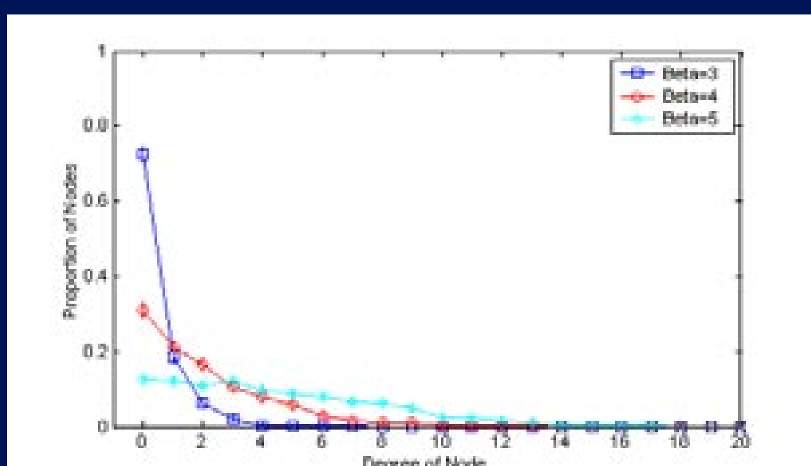
- 10,20,40,80 nodes distributed randomly on surface
- 100 trials per condition

Compute network topology

- Line-of-sight visibility used as connectivity metric
- Compute degree distribution

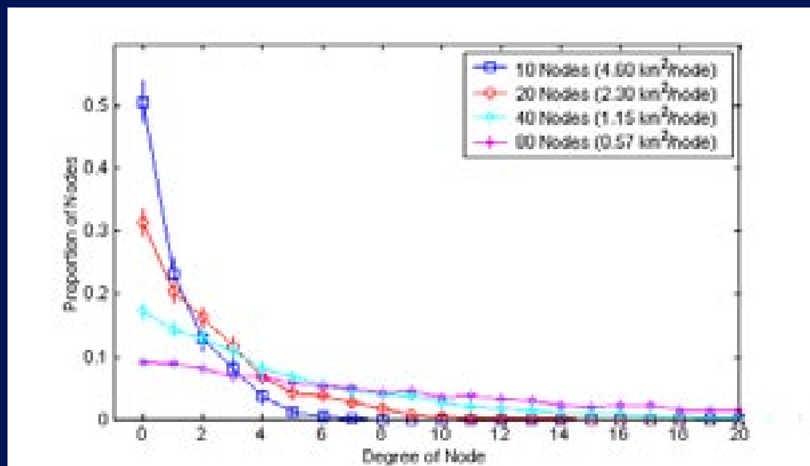
Network Topology Study

Results (Topography Study)



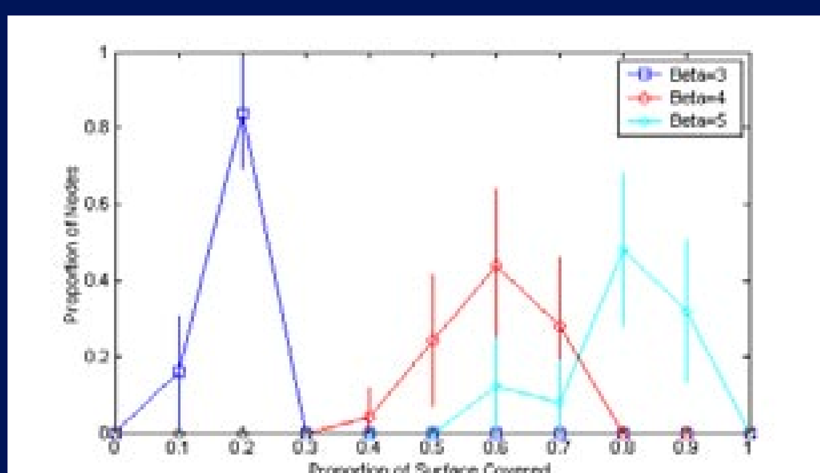
Network Topology Study

Results (Node Density Study)



Network Topology Study

Results (Surface Coverage, 25 trials)



Trade Study Process

1. Develop functional requirements
2. Build an environment
   - Create a digital elevation model
   - Use a representative surface model
3. Define node distribution and evolution
   - Initial delivery/deployment mechanism
   - Evolution of distributed system over time
4. Determine network topology of the system
   - Line-of-sight connectivity metric
   - Range limitations

Trade Study Process (2)

5. Apply analysis tools
   - Surface visibility and coverage
   - Reachability
   - Link budgets, cost of message delivery
6. Evaluate other trades

Node heterogeneity, maximal data flow, frequency allocation, routing algorithm testing

7. Evolve the system
   - Define an operational process model
   - Evolve node internal states (internal resources, goals, models)
   - Evolve node external states (e.g., position, orientation)
8. Evolve model of the environment
9. Repeat process starting at #4 as necessary.

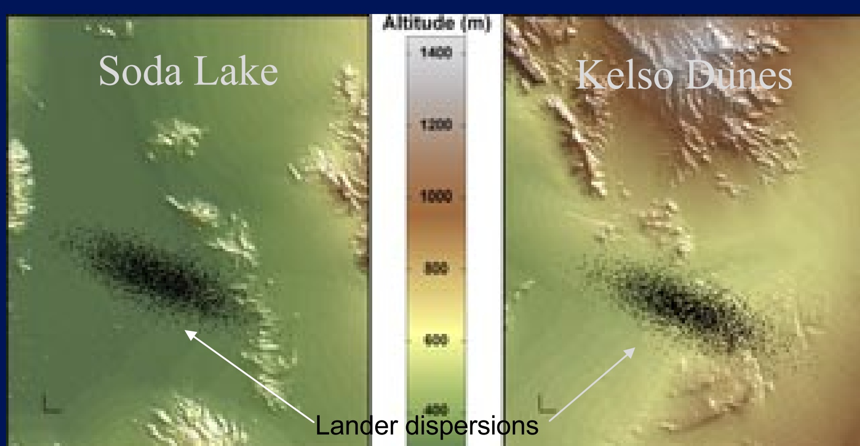
Lander and Sensor Network Example

A Mars Lander is to serve as a communication trunk for a sensor network to be deployed on an ancient lakebed. Two sites are under consideration: a smooth flat lakebed, and an area of sand dunes.

This example explores the factors involved in designing the system to meet a single requirement, that 90% of the sensor nodes should be reachable by the lander with a 90% probability.

Lander and Sensor Network Example

Representative Surface: Mojave Desert



Lander and Sensor Network Example

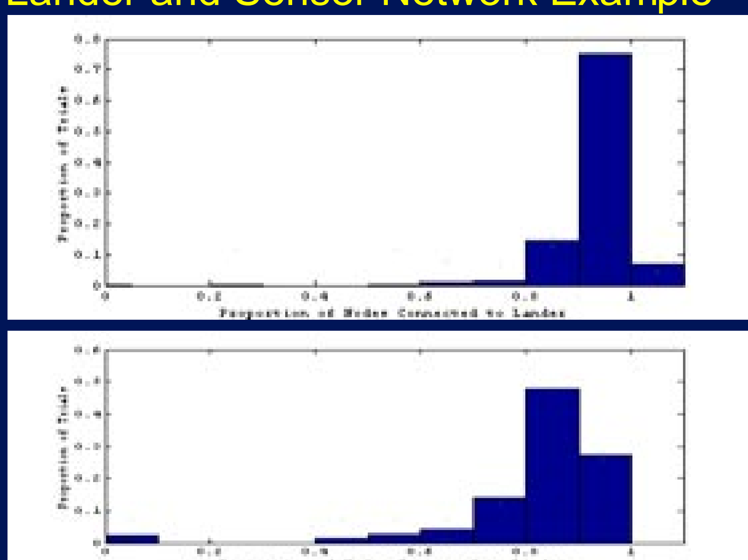
Parameters

- 300 lander positions
- 100 nodes
- 2 surfaces (Soda Lake, Kelso Dunes)

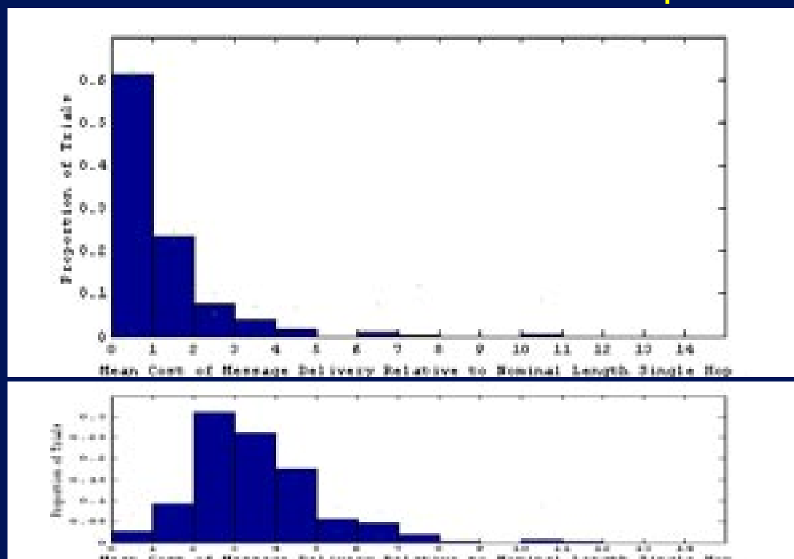
Analysis

- Proportion of nodes connected to lander
- Mean cost of message delivery
  - Connectivity graph: assign edge cost $C = (r/d)^2$
  - r=distance between nodes
  - d = nominal distance between nodes
  - m=space loss exponent=2 (free space).

Lander and Sensor Network Example

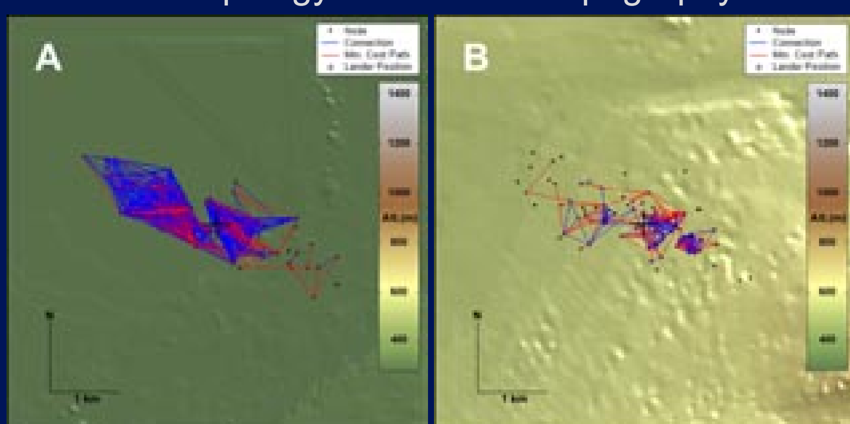


Lander and Sensor Network Example



Lander and Sensor Network Example

Network topology: sensitive to topography.



Soda Lake

Kelso Dunes

Conclusions

- Distributed Systems Can be Modeled
  - Environment model: digital elevation model
  - Connectivity model: line-of-sight
- Many trades exist
  - Many hierarchical layers
  - Optimization very challenging
- Connectivity and surface coverage strongly affected by topography and node density.

Conclusions (2)

- Trade study process
  - Provides approach to examining trades
  - Does not specify optimization process
- Lander example
  - Illustrates effect of landing site selection (topography differences)
  - Increased mean cost of message delivery, lower connectivity for surfaces of increased roughness
- Need better connectivity metric and environment models
- Need better dynamic system model (true multi-agent system)

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